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Open and Closed Magnetic Confinement Systems: Is There a Fundamental Difference in Their Transport Properties?

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OPEN AND CLOSED MAGNETIC CONFINEMENT SYSTEMS: IS THERE A FUNDAMENTAL DIFFERENCE IN THEIR TRANSPORT PROPERTIES?

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Abstract

The results of five decades of experimental investigations of open-ended and closed magnetic confinement geometries are examined to see if intrinsic topology-dependent differences in their cross-field transport can be discerned. The evidence strongly supports a picture in which closed systems (stellarators, tokamaks, reversed-field pinches, etc.) are in all cases studied to date characterized by some level of plasma turbulence, leading to substantial deviations from purely "classical" cross-field transport. This transport is often describable as a "Bohm-like" scaling with plasma temperature and magnetic field intensity. By contrast, open systems have in many significant examples been able to approach closely to classically predicted cross-field transport, including cases where the transport appeared to be more than five orders of magnitude slower than the Bohm-diffusion rate. To explain these differences the following tentative hypothesis is put forward: The differences arise from two sources: (1) differences in the instability driving terms arising from "free-energy" sources, such as current flow along the field lines, etc. and, (2) differences in the nature of the boundary conditions for the various unstable waves that may be stimulated by these free energy sources within the plasma. By analogy with a laser, closed systems, with their flux tubes returning on themselves, resemble a ring resonator, while open systems either have or can be arranged to have absorptive (or low reflectivity) end boundary conditions for unstable waves. It is suggested that if the hypothesis is a valid one it further enhances the desirability of devoting more effort to the investigation of open-ended systems than is now being allotted.

I) Introduction

The 50-year-long history of research into the confinement of plasma in magnetic fields should have taught us one clear lesson: There is a fundamental difference in the character of plasma confinement between that in so-called "closed" systems, such as the tokamak, the stellarator or the reversed-field pinch, and "open" systems, such as those based on the use of the magnetic mirror principle to provide axial confinement. Closed systems, with no known exceptions, show confinement that is dominated by turbulence-related processes, rather than by "classical," i.e., collision-related, processes. As a result, to achieve confinement adequate for fusion power purposes in, for example, the tokamak requires that it be scaled up in size and power level to the point that its ultimate practicality as an economically viable source of fusion power is open to question. By contrast, from earliest days there have been examples of open systems where turbulence, if present at all, is at such a low level that only collision-related processes play a significant role in determining the confinement. Given these insights we shall in this paper advance an hypothesis, and then attempt to validate this hypothesis through examples drawn from past and present magnetic fusion research experiments and from the theoretical underpinnings of that research.

The hypothesis has two parts. These are:

- Owing to their topology, closed systems are inherently prone to turbulence-induced plasma losses.

- Conversely, the topology of open systems allows the possibility of operation in plasma regimes with particle transport that approaches classical collision-induced loss rates.

If this two-part hypothesis is indeed valid it bears directly on the present situation in magnetic fusion research, as follows: As mentioned previously, closed systems such as the tokamak have, through decades of research, been shown to have particle and energy cross-field transport rates that are far higher than those that would arise from classical, i.e., collision-dominated, processes alone. In addition, the plasma energy density relative to the magnetic field energy density, i.e. the plasma "beta" is itself limited to a few percent by turbulence effects. As a consequence the projected size of a fusion power system based on the tokamak is very large, raising questions as to its likely economic viability.

The growing awareness of this situation for the tokamak has led significant numbers of the fusion research community to initiate a search for smaller and simpler approaches. While for many researchers the "search for new approaches" means to them finding ways to reduce the size of closed systems, for example through investigating geometries such as the spheromak, the implications of the hypothesis presented here should be a matter of concern to them.

In the sections to follow we will briefly review the historical record of confinement in closed systems and cite some theoretical results that may help explain these observations. We will then do a similar review of open system confinement systems and again provide a summary of theoretical arguments in support of these results. We will conclude by suggesting the value of including new types of open systems in the ongoing search for better approaches to magnetic fusion.

II) Closed Systems: The Historical Record

One of the earliest-invented closed confinement concepts was the stellarator, invented early in the 1950's by Lyman Spitzer of Princeton University. Its concept was based on a clever solution to a now well-known fundamental problem associated with the confinement of plasma in an externally generated magnetic field in toroidal geometry. This problem is the following one: If the confining field has only a toroidal component, i.e., if it is generated by a solenoidal coil bent into a circle to form the torus, it cannot contain a plasma in pressure equilibrium within the torus. The simple physics reason behind this counter-intuitive result is that the magnetic field configuration that we described has a negative gradient of intensity in the outward direction. The result: the plasma simply slides "downhill" on this gradient until it hits the outer wall of the toroidal chamber. Spitzer's initial clever solution to this problem was to twist the torus into the form of a figure-8. Now, as the particles are guided along a field line, the plasma particles alternately find themselves nearer to the inner wall and then the outer wall of the chamber, so that their radial drifts cancel out on average, thus permitting a confined state to exist.

Although the stellarator idea was later modified (by the use of special coil configurations) to permit the use of a simple doughnut-chamber vacuum vessel, the first results in the tests of the stellarator principle at Princeton were performed in the figure-8 geometry. Before describing the results of these first tests we will cite the confinement standard that Spitzer had established theoretically and against which the experimental results would be compared. In a closed magnetic field system such as the stellarator the only mode of egress for trapped particles is across the field lines. Thus, the critical issue here is the rate at which trapped ions and electrons will diffuse across a magnetic field.

The magnetically confined plasma regime that Spitzer considered is the one that would be encountered in a fusion power context: Specifically, it is the regime in which the ion and electron kinetic temperatures are high enough (many kilo-electron-volts), and the plasma density is low enough (of order 10^{20} m^{-3}) that the mean-free-path for inter-particle collisions is very large compared to the dimensions of the plasma. At the same time, the magnetic field is strong enough (typically 5 Tesla or more) that the gyro-orbit diameter of the ions and electrons is very small compared the diameter of the plasma column. In such a situation particle diffusion across a magnetic field can in rough approximation be considered to be a modified random-walk, one in which the frequency of the steps is equal to the inter-particle collision frequency. In a different way of looking at the problem, the diffusion can be viewed as the result of energy dissipated by the electrical resistivity of the plasma (arising from electron-ion collisions), with the needed energy being supplied by the expansion of the plasma. This type of diffusion is ambipolar in nature, that is, the ions and the electrons diffuse together, the faster-diffusing electrons being held back by the ions, acting through an electrical potential. As calculated by Spitzer [1], this "classical" diffusion rate is given by the expression:

$$v_d = -\frac{\eta}{B^2}\nabla p \qquad \text{m/sec.} \qquad (1)$$

where η (ohm-meters) is the electrical resistivity of the plasma for currents transverse to the magnetic field. For a plasma with ions of charge number Z, for example, Spitzer's value for this resistivity is:

$$\eta = 3.3 \text{ x } 10^{-9}\frac{Z\ln(\Lambda)}{(T_e)^{3/2}} \qquad \text{ohm-m.} \qquad (2)$$

Here T_e is the kinetic temperature of the electrons in kilovolts, and $\ln(\Lambda)$ is the usual Debye screening distance factor, of order 20 for fusion plasmas.

When fusion-relevant plasma parameters are inserted into Equations 1 and 2 the Spitzer-predicted radial diffusion velocities are very slow, reflecting the low collisionality of hot plasmas. For example, inserting 10 keV for the electron temperature, Z =1, n_e = 10^{20} m^{-3}, B = 1.0 Tesla, and assuming a characteristic distance for the pressure gradient of 0.1 m. there results a snail-pace diffusion velocity of approximately 3.2 x 10^{-3} m/sec. At that rate of diffusion, it would take about 30 seconds to double the gradient distance, implying more-than-adequate confinement times for fusion power purposes. It was from this optimistic picture that the Princeton Stellarator Program was launched. It was argued that even if the Spitzer-predicted cross-field diffusion rate was two orders of magnitude too optimistic, the projected plasma confinement times in a full-scale stellarator would be long enough for fusion power purposes, even for plasma radii as small as a meter or so.

What was actually found when the first stellarator was put into operation was plasma confinement that was far poorer than even the researchers most "conservative" projections. Not only was the confinement poorer, but it scaled in all the wrong ways. Where the Spitzer rate decreases with plasma temperature, varying as $T^{-1/2}$, in the experiments the diffusion <u>increased</u> linearly with temperature: The hotter the plasma became, the worse the confinement. Furthermore, where the Spitzer diffusion rate predicts confinement times increasing as the square of the magnetic field intensity, in the experiments it increased only linearly with B. This "non-classical" behavior, one which persisted throughout the early days of stellarator research, was called "pump-out." Its characteristics can be seen in a plot of experimental data [2], taken on the large Princeton Model C stellarator, and reproduced in Figure 1. The plot shows the scaling of confinement time, varying as B/T_e over the range of a factor of 10 in electron temperatures, from 3 to 30 electron volts. The scaling with temperature according to the classical rate is also shown on the plot.

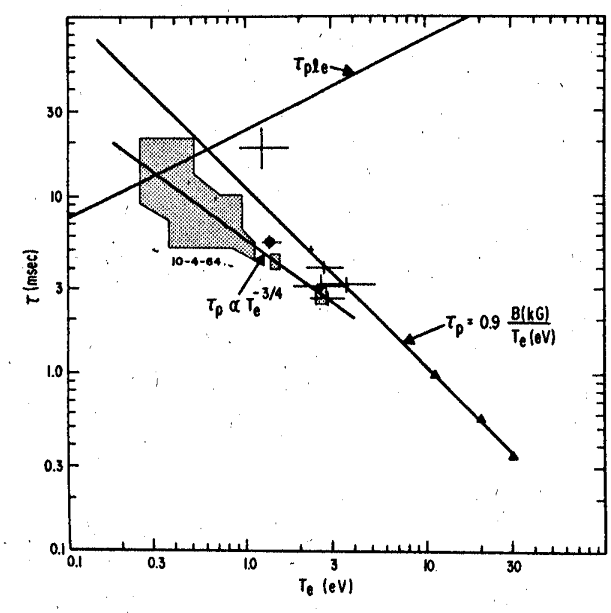

Figure 1: Confinement time <u>vs</u> electron temperature in the Model C Stellarator

As we now are aware, these observations on the early stellarators were harbingers of a long-continued saga in magnetic fusion research, one that continues to this day. Upon analyzing all the data it was recognized that all the observations were consistent with an earlier-predicted scaling, the "Bohm" diffusion rate, postulated years earlier in unpublished work by David Bohm. Bohm was attempting to explain some anomalies in the performance of the so-called "Calutron" isotope separation devices developed during World War II at Earnest Lawrence's Radiation Laboratory (as it was then called) in Berkeley. Based on simple considerations, namely that instability-induced fluctuations would grow until they reach a limiting amplitude, Bohm postulated that diffusion across a magnetic field would be governed by the diffusion coefficient (kT_e in keV, B in Tesla).

$$D_b = 62.5\ (kT_e / B) \quad m^2\, sec^{-1} \qquad (3)$$

Inserting the parameters of the former example, namely $kT_e = 10$ keV, B = 1.0 Tesla, and a gradient characteristic distance of 0.1 m., we find for the diffusion velocity 6.3×10^3 m/sec, i.e., more than five orders of magnitude larger than the Spitzer-predicted value!

As was noted, the Bohm-diffusion rate corresponds to a case where turbulence has reached a fully saturation-limited value. In the Model-C experiment this circumstance arose because of the presence of a spectrum of instabilities. In the years following these early experiments there began the long, slow, march associated with finding ways to reduce the turbulence levels, in the drive toward improving confinement times to the level that would be required for fusion. As matters now stand in the present-day stellarators, improvements in transport rates (relative to the Bohm rate) by nearly two orders of magnitude have been achieved. However even this level of improvement over the Bohm value implies transport coefficients that are much larger than the classical value, i.e., rates that are still dominated by turbulence rather than by inter-particle collision rates. These results also imply that the size of any power-producing stellarator would have to be very large, with plasma diameters of meters, and overall chamber lengths of tens of meters.

The stellarator was one of the earliest closed confinement-geometry systems to so clearly show the effects of instability-driven turbulence on confinement. However, the history of plasma confinement research in other closed-geometry systems, without exception it appears, has shown particle and energy confinement times degraded substantially from that expected from classical predictions, i.e. those predictions based solely on inter-particle collisions.

The appearance of the tokamak on the scene in the early 1960s gave new hope to the proponents of closed-geometry systems in that the confinement in those early tokamaks was clearly better than that in the early stellarators. At that time, with the Bohm diffusion law as the measuring stick, tokamak confinement was characterized as being, for example, "one-tenth of Bohm," etc., indicating the improvement obtained over fully developed turbulence-dominated diffusion. Even so, the measured energy and particle transport rates were still much larger than those calculated for a quiescent plasma.

Over the three decades that followed the first tokamak experiments, a better understanding of the processes driving turbulence in the such devices resulted in substantial gains – another order of magnitude – in reducing transport rates. However, as of today it is evident from the data that the energy and particle transport in tokamaks is still dominated by turbulent processes, driven by persistent instabilities. Even the discovery of the "H-mode" (for High-Confinement mode, which results in a factor of two increase in confinement time relative to the usual "L-mode" (for Low-Confinement mode), did not change this conclusion. The H-mode is in fact a regime that still clearly exhibits well-developed turbulence. For example, Figure 2 reproduces some experimental traces of electron density, electron temperature, fluctuating magnetic field amplitudes, etc. obtained in the large Princeton TFTR tokamak [3], before and following the transition to H-mode behavior. The presence of large-scale turbulent effects is evident, even in the "good-confinement" mode.

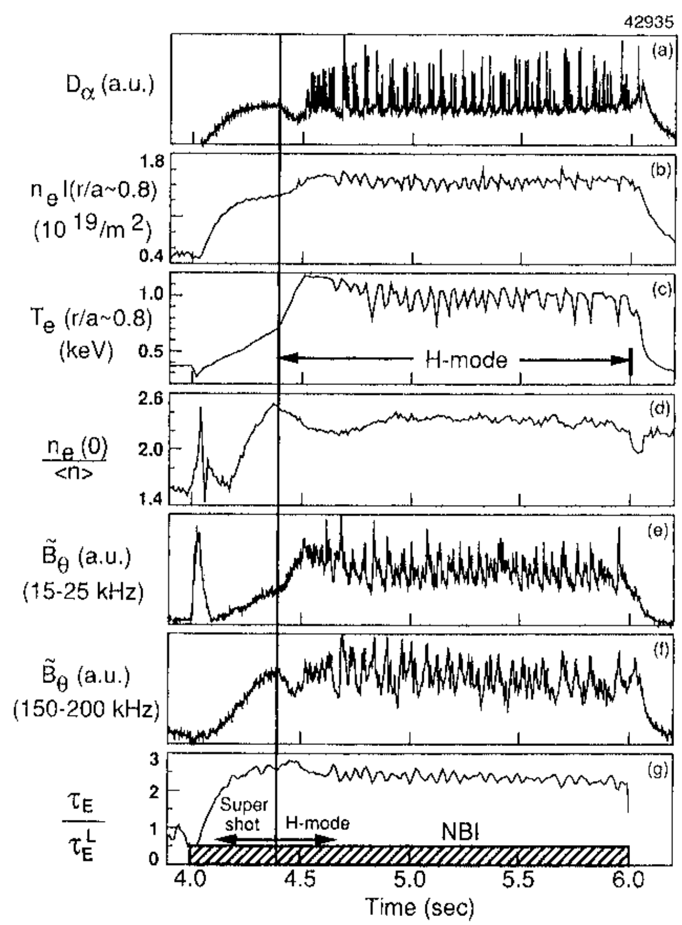

Figure 2: Fluctuations in TFTR accompanying H-mode confinement regime

That the presence of turbulence, such as that that is evident in the TFTR data, has a direct influence on transport is evident when its dependence on temperature is measured. Classically the confinement should improve monotonically with plasma temperature, reflecting the decrease of collision cross-sections with increasing temperature. In TFTR, as also seen in other tokamaks, exactly the opposite effect occurs. Figure 3 reproduces TFTR data for the electron and ion transport coefficients as a function of the electron temperature. The trends in transport coefficients are clearly upward, and at an even faster rate than the linear dependence predicted by the Bohm formula.

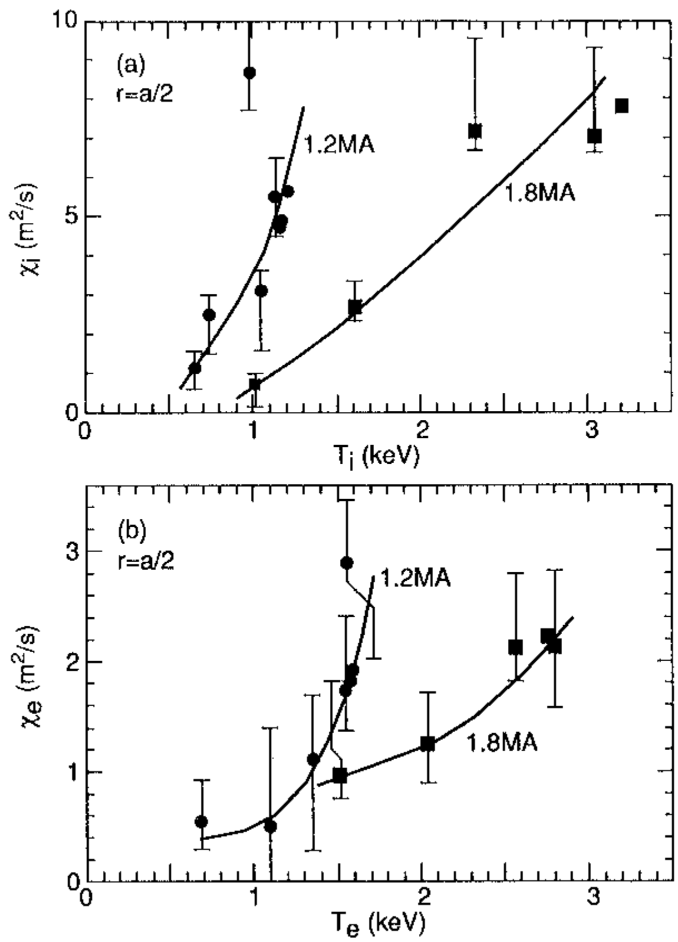

Figure 3: Ion and electron transport coefficients in TFTR as a function of T_e

There is yet another characteristic of the confinement in closed systems that bespeaks their susceptibility to unstable behavior, namely, the strong limits on the plasma beta value that are encountered, typically limiting the plasma pressure to a few percent of the magnetic field pressure. When attempts are made to increase the pressure beyond these values, the level of instabilities grows, causing unacceptable levels of cross-field transport. The most extreme example of this effect is the disruption phenomenon that occurs in tokamaks, when the entire plasma is dumped to the walls, sometimes with severe damage to the apparatus. Though progress has been made in understanding these beta-related instabilities in closed systems, it seems clear that they will continue to represent a limitation on the economic viability of these systems, since low beta values, together with the effects of turbulence-enhanced transport, dictate that these systems must be large in order to yield net fusion power at useful power levels.

Examination of the many-decades-long experimental record of the tokamak shows that the picture is a very complex one, thus far defying a complete theoretical analysis. The plasma instabilities that are ubiquitous in tokamaks appear to be of several varieties, ranging from those of MHD origin to ones driven by the necessary presence of radial temperature gradients in any closed-field system where the plasma terminates on nearby bounding surfaces. The universally accepted conclusion from this situation is that all tokamaks must live with turbulent regions in their plasmas, so that as fusion power systems their minimum size will be dictated by the role of turbulence, and not by classical processes.

If we turn from the tokamak to other closed systems, a very similar picture emerges vis-à-vis the presence of well-developed turbulence and its effect on confinement and transport. For example, in the RFP (Reversed-Field-Pinch) the confinement times seem to be essentially those predicted by the Bohm formula, and the plasma itself appears always to exist in a "burbling" state. This state seems to be one associated with a competition between the self-consistent "Taylor state" [4] which is required for equilibrium, and the effects of turbulence-enhanced diffusion.

In summary, examining the historical record, only a sampling of which we have discussed here, lends support to the first part of our two-part hypothesis, namely, that closed systems are inherently prone to instability-driven turbulent processes.

Before we turn to a discussion of the origins of the turbulence in closed systems such as the stellarator, the tokamak, or the reversed-field-pinch, it is important to make clear that the presence of turbulence and the limitation of beta values that is endemic to these devices does not at all preclude them from becoming useful fusion-power-producing systems. What is does say, however, that all such devices will have a size that is much larger than the size that they would have (to achieve a net fusion power release) if the turbulence and strong beta limits were not a fact of life for them. This being the case, it would seem fruitless to hope for some "breakthrough" in this class of device that would suddenly shrink its size to the size that a turbulence-free, high-beta, confinement system could have.

III) Closed Systems: Sources of Plasma Turbulence

Although the anatomy of the turbulent states in closed systems such as the tokamak has thus far defied detailed theoretical analysis, it is possible to identify some potential sources of the turbulence, and some of the topology-related circumstances that promote it. When we make a comparison between closed systems and open ones, we will note that many of these instability-drivers are not present in a wide class of open-ended systems.

One inescapable driving source in all closed-topology systems is the presence of radial temperature gradients near the periphery of the plasma. In closed systems of toroidal topology there is only one channel of plasma loss, i.e., across the field lines to the chamber boundary. Since the plasma temperature must fall to that of the wall in the plasma sheath regions it follows that there will always exist a negative temperature gradient over some fraction of the plasma radius near the wall. This circumstance, as theory shows, can stimulate plasma turbulence.

A second source of turbulence resides in the presence of high-order MHD modes that may be stimulated by resonant cross-coupling between the modes and by particle drifts across the magnetic field. The MHD mode structure in tokamaks, stellarators, and reversed-field-pinches is very complex, and there exists a spectrum of driving mechanisms that may stimulate these modes, causing transport, that in turn may continue to feed the instability at some level.. An example of this effect is to be seen in "mode-locking" effects on persistent unstable MHD modes seen in the RFP (and also in other closed-field devices). Figure 4 shows the appearance of such a mode in the MST RFP [5].

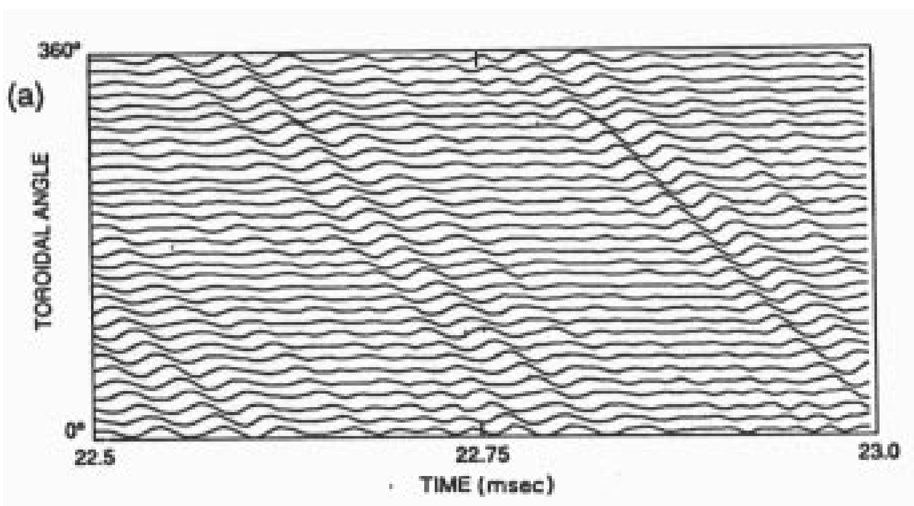

Figure 4: Mode-locked MHD waves in the MST Reversed-Field Pinch experiment

Another, and potentially important driving source for plasma instabilities in closed-line systems is the existence of electrical currents parallel to the direction of the magnetic field lines. Such currents exist at some level in all closed-field devices, particularly in the tokamak, where such currents are essential to the existence of an equilibrium state. It is well known that parallel currents can stimulate certain classes of instability that feed off departures from a maxwellian particle distribution. In extreme cases the current can cause the rapid disruption of the entire plasma.

Finally, inherent to toroidal closed systems, and particularly apparent in the stellarator, are particle drifts across the confining field that occur in these devices for certain classes of particles. Such drifts arise from the geometry of the fields and thus cannot be avoided. They are the source of the parallel currents just alluded to, and can themselves be the source of instabilities in closed-field systems.

Given that there are a variety of sources of instability, we can examine as to whether the closed-field geometry of the tokamak and other toroidal confinement systems also plays a role in the development of turbulent states. Here the earlier-cited example, illlustrated in Figure 4, of mode-locking, can give us a clue. To make an analogy to another system that taps the free energy associated with departures from a maxwellian equilibrium state, consider a ring laser. This type of laser, one that does not require end mirrors for its action, depends on the continued amplification of an initial perturbation, the frequency and phase of which is locked in by propagation in the ring geometry. In a similar way, even weakly unstable waves in a toroidal plasma can grow until they reach a limiting amplitude as they propagate around the torus. The effect we are here describing is shown schematically in Figure 5, which depicts a slow-growing wave propagating around a torus.

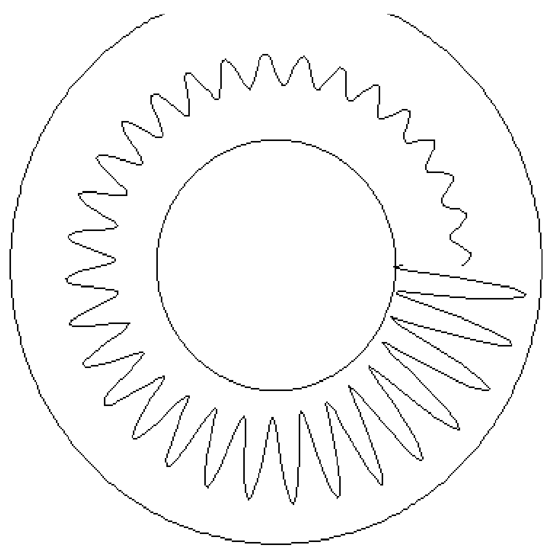

Figure 5: Schematic illustration of a growing unstable plasma wave in a torus

Although these are qualitative arguments, it is apparent that closed systems of toroidal geometry should be (and indeed are) prone to the development of plasma turbulence. This turbulence is the end result of plasma instabilities that are fed from various sources of free energy, some of which are inherent to the existence of pressure and diffusion equilibrium in toroidal geometry.

IV) Open Systems: The Historical Record

When we examine the historical record for open-ended plasma confinement systems a very different picture from that of closed systems emerges. There are some clear examples from early work of cases where open-ended systems confined plasmas where the cross-field diffusion, if it deviated at all from classical rates, was five or more orders of magnitude slower than the Bohm rate. One such example was the "Table Top" experiment at Livermore in the 1960s. In this experiment a plasma gun injected a microseconds-long burst of plasma into an evacuated chamber, within a time-rising magnetic field, in the form of an axially symmetric mirror cell with a mirror ratio of 2. The initial magnetic field was low, 10 to 20 Gauss, rising to about 10,000 Gauss in 500 microseconds, at which point the coil was shorted so that the field decayed with a time constant of a fraction of a second. The rising field captured a portion of the injected plasma burst, and compressed and heated it to form a spindle-shaped plasma with a radius of about 2 centimeters, and a length of 20 cm. or so. The measured electron temperature was about 20 keV, and the peak plasma density approached 10^{14} cm^{-3}.

As to the behavior of the confined plasma, it was observed to be "metastable" in that it remained centered unless triggered into a rapid m=1 transverse drift by electrical transients. When in its metastable state its radial diffusion was measured by profiling its end loss rates as a function of radius. What was observed was that the radial diffusion, as measured over several milliseconds, was almost undetectably small, being at least 5 orders of magnitude slower than the rate predicted by the Bohm formula for that electron temperature and confining field [6]. Figure 6 shows a decay curve of the electrons, smooth and at a rate that was, within the accuracy of the measurements, consistent with collision-produced end losses through the mirrors. Figure 7 illustrates three measurements of the plasma radial profile, taken at intervals of a millisecond. As can be seen the rate of diffusion of the electrons across the magnetic field inferred from these data was almost too small to measure.

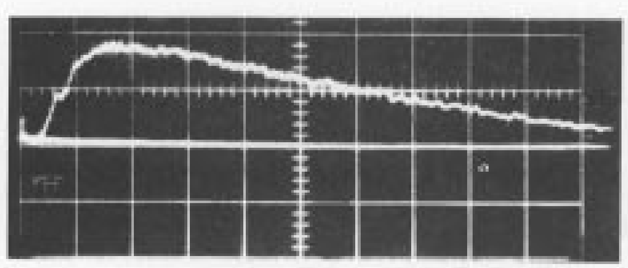

FIG. 1. Typical oscilloscope trace of a scintillator photometer signal — sweep time 5 milliseconds.

Figure 6: Plasma decay in Table Top (reproduced from 1960 Phys. Rev. Letters article)

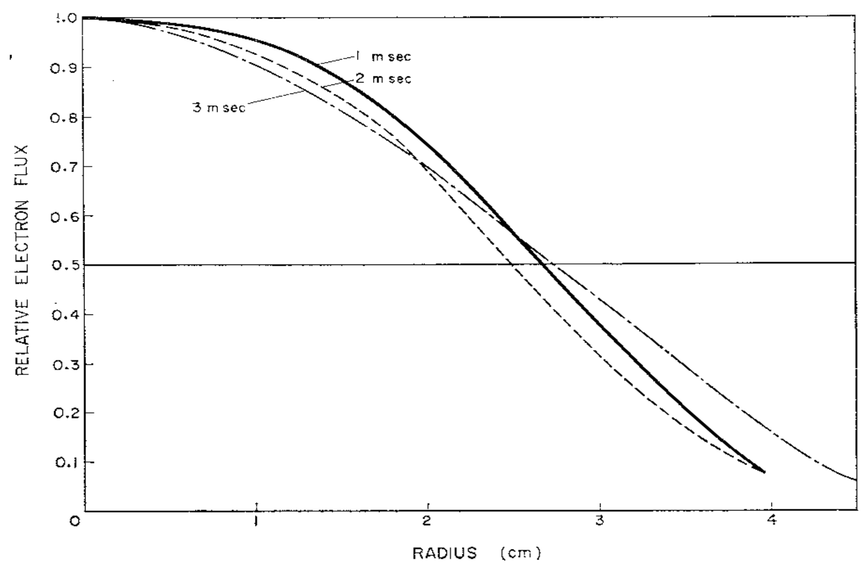

FIG. 11. Normalized radial distribution of plasma as a function of time.

Figure 7: Plasma profiles in Table Top (reproduced from 1960 Phys. Rev. Letters article)

At the time the metastable nature of the plasma equilibrium in the supposedly MHD-unstable axially symmetric mirror cell of Table Top was never totally explained. However, some interesting further investigations of this phenomenon were made by Perkins and Post [7] who made measurements that followed the plasma spindle (after triggering) as it spiraled out in radius, apparently intact, until it reached the chamber wall (glass, covered by a thin evaporated film of metal), where it continued to rotate for several milliseconds until it was, it appeared, abraded away by contact with the wall.

A few years after the Table Top experiments, in 1968, another example of a hot plasma confined in an open-ended system with radial transport that clearly disagreed with the Bohm formula was confirmed. In the 8-meter Theta Pinch experiment at Culham, England, careful measurements were made of the rate of cross-field diffusion, both as the rate of the diffusion and as to the equilibrium radial profile of the plasma. The diffusion rate that was found, measured as a function of plasma collisionality, is shown in Figure 8. As can be seen, the plotted points agree with the classical rate, and clearly disagree with the Bohm rate, or even 1/10th of the Bohm rate. The measured radial profile of the plasma is shown in Figure 9. As can be seen, it agrees with the classically predicted one, and disagrees with the profile expected if Bohm diffusion dominated.

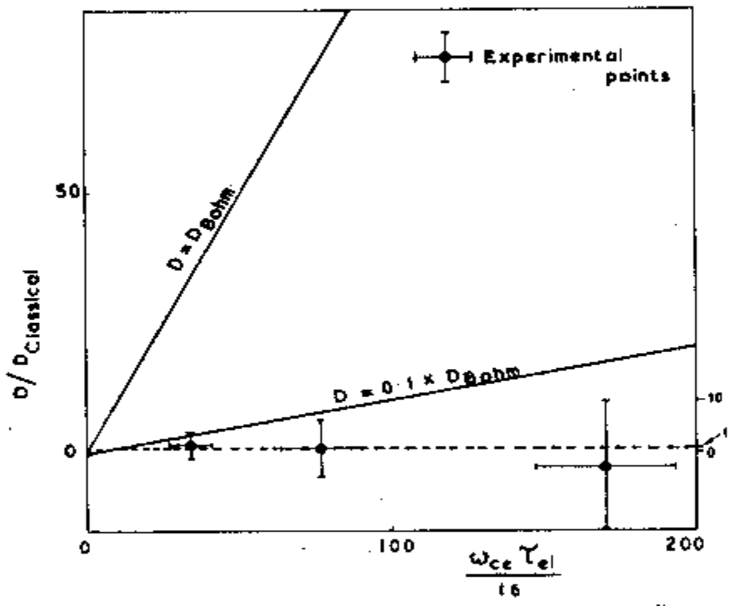

Figure 8: Ratio of observed diffusion to classical diffusion as a function of normalized electron-ion scattering times for the Culham 8 meter theta pinch experiment

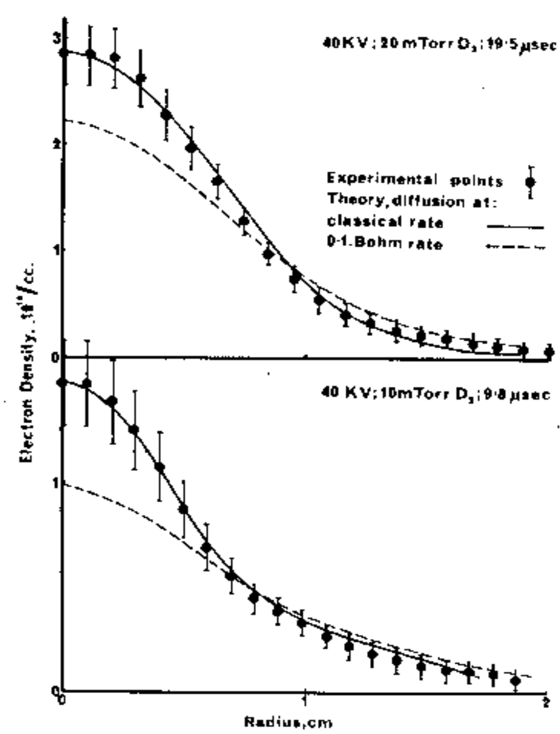

Figure 9: Plasma radial profiles in Culham 8-meter theta pinch

As well as providing examples of confinement not dominated by turbulence, the history of research into open-ended systems of mirror geometry is replete with cases where plasma instabilities of the "loss-cone" type led to rapid escape of the plasma, usually out the mirrors. However, as years of research proved, and as theory verified [8], these instabilities, as their name suggests, arose from distortions in the velocity-space distributions of the ions caused by the existence of the mirror loss cone. When this fact was understood, and when proper measures were taken (for example, stabilization by "warm plasma" streams), the confinement times approached closely those predicted by considering collisional effects alone. One classic experiment illustrating this point was the 2XIIB experiment at Livermore [9]. In this plasma, upon using a warm plasma stream derived from a plasma gun and a gas box to stabilize the loss-cone instabilities, together with neutral beam injection at 10 to 20 keV, a dense (10^{20} m^{-3}), hot (up to 20 keV) deuterium plasma was built up and stably confined with no discernable level of turbulence. Figure 10 shows the buildup of plasma, in agreement with trapping theory and classical loss rates, after turning on the neutral beam sources. Also shown is the onset of instability, early on in the buildup, in the absence of the warm plasma stream.

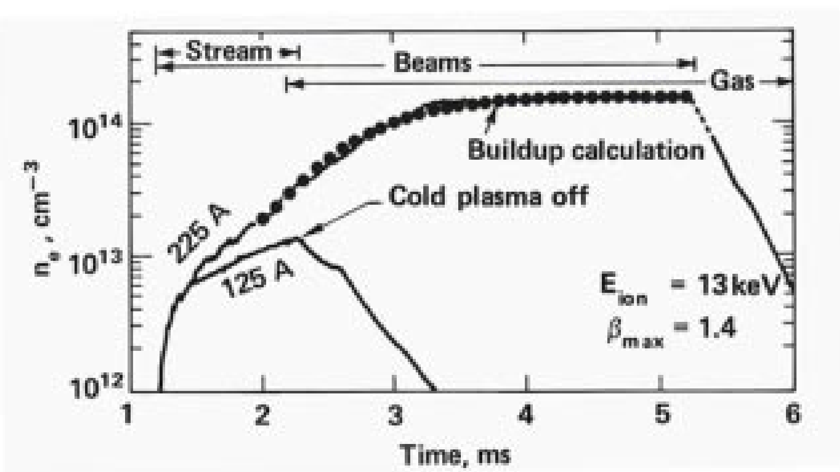

Figure 10: Plasma buildup in 2XIIB showing close agreement between experiment and theory when warm plasma stabilization was used.

A further remarkable result from the 2XIIB experiment was the high value of the plasma beta (approaching 1.0 against the external field) that was achieved, with no evidence of the strong turbulence that occurs in closed-geometry systems such as the tokamak and the stellarator when the beta values rise above a few percent. That high-beta plasmas could be MHD-stable in open systems had been predicted theoretically [10], and this prediction was borne out by the experiment.

Over the years following the 2XIIB experiment, the tandem mirror idea arose, and the efficacy of axial ion confinement by ambipolar potentials was demonstrated. Again a close agreement between the theory of potential confinement and the measurements was found, further evidence of confinement in an open system not dominated by turbulence-produced losses. Figure 11 reproduces a plot of data taken on the Gamma 10 tandem mirror experiment at Tsukuba, Japan [11], showing close agreement between axial loss times and the Pastukhov-Cohen theory. [12]

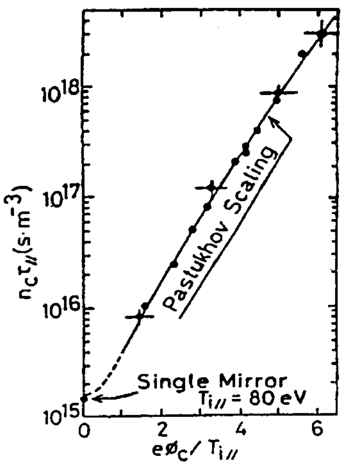

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Figure 11: Plot of axial nτ vs plasma potential for Gamma 10, theory and experiment

More recently there have been some very significant measurements taken with the Gas Dynamic Trap (GDT) Experiment at the Budker Nuclear Physics Institute in Novosibirsk, Siberia. In this experiment an axisymmetric mirror cell with high mirror ratio is used to confine a high-beta (30 percent) plasma, stabilized against MHD modes by the effluent plasma as it flows through the "expander" regions outside the mirrors [13]. Into this mirror-confined plasma are injected high-energy neutral beams., to create a "sloshing ion" distribution by reflection at the mirrors. Careful study of this plasma shows that its confinement is "classical" in that there is no evidence of departures from classical rates of diffusion of the ions across or along the field lines, the data agreeing closely with the theory [14]. To quote from the article: "The comparison between the measured and calculated energy content of fast ions shows that within the accuracy of the measurements the experimental and simulated data are identical."

The conclusion to be drawn from this brief historical review of open-system confinement research is that there are clear examples of such systems where the radial transport was clearly much less than that predicted by the Bohm formula, and where the plasma itself appeared to be quiescent, decaying smoothly with no evidence of the turbulent behavior characteristic of closed systems. When turbulence did appear, it was identified with instabilities of loss-cone origin, understood theoretically, and controlled by means predicted by theory. In short, the historical record lends strong support to the second part of our hypothesis, namely, that: "….the topology of open systems allows the possibility of operation in plasma regimes with particle transport that approaches classical collision-induced loss rates."

V) Open Systems: Possible Explanations of the Experimental Results

In this section we will cite some aspects of the theory of open systems that provide support for the second part of our hypothesis. They also provide a basis for optimism with respect to the future of such systems as fusion power systems, optimism that still must be tested against reality.

An important factor that enters into the confinement picture, particularly for axi-symmetric open system, is the constraint on particle excursions associated with the two adiabatic invariants, magnetic moment, μ, and the longitudinal action integral, J. As shown many years ago by Teller and Northrop [15], these invariants constrain trapped particles to move on closed drift surfaces. This circumstance implies that in the absence of other processes, trapped particles will be confined "forever." The power of these invariants was illustrated graphically in the "Argus" experiment. In this experiment, as proposed by Christofilos, high-energy electrons were injected into the earth's Van Allen belts by detonating a rocket-launched nuclear explosive. A decade later the presence of these trapped electrons could still be detected!

In an axially symmetric open confining field the particle drifts are also axisymmetric so that these drifts do not of themselves act as a driving source for cross-field diffusion. This situation is to be contrasted to that in closed systems such as the stellarator where there are classes of particles that have persistent drifts across the confining field that would take them out of the system in the absence of collisional de-trapping effects.

The possible role of parallel currents in driving instabilities in closed systems such as the tokamak has been earlier mentioned. However, in axially symmetric open systems these drifts do no give rise to parallel currents. This result can be shown theoretically [16] for a wide class of pressure equilibrium solutions, those that can be written as a function of the flux surfaces, ψ, and the magnetic field, B, i.e., $p(\psi,B)$. For such distributions the condition for zero parallel currents everywhere within the plasma is given by the equation:

$$\mathbf{n}\cdot[\mathbf{B}\times\nabla(B)] = 0 \qquad [4]$$

Here **n** is a unit vector normal to the flux surface. Since the term in the brackets is a vector that is everywhere tangential to that flux surface, its dot product with **n** is identically zero everywhere within the plasma. Thus in this type of open system there are no parallel currents in equilibrium, even at very high beta values.

There is yet another characteristic of open systems that allows them to avoid one of the significant driving terms for instabilities in closed systems. This characteristic has to do with the radial boundary conditions of the confined plasma. Since there are two loss channels in open systems, one across the field, and one along the field, it is not necessary, in fact it is seldom the case, for the plasma to terminate in the radial direction on a bounding surface. The confined plasma column can exist with a radial boundary that is well inside the surface of the confinement chamber. Thus there is no requirement, as there is with closed systems, that there be a negative temperature gradient in the plasma as its radial boundary is approached. In fact, in principle the radial variation in the plasma temperature can be zero, or could be principle be inverted, if this became desirable to suppress certain classes of drift instabilities. Not only is the temperature gradient subject to control, but the radial distribution of the plasma potential can be controlled by grading the potential of the bounding surfaces at the chamber ends, as was demonstrated in Gamma 10 [17], where this technique was used to suppress certain drift modes that occurred in the non-axisymmetric geometry of that device.

Finally, in pursuing the reasons for the difference between closed and open systems it is of value to reintroduce the qualitative idea of the laser amplification of instabilities. Such processes are ones that may play a significant role in closed systems, where the analogy of the ring laser was introduced. Pursuing this analogy, open systems can be thought of as resembling a conventional linear laser with end mirrors. Such lasers can only operate if two conditions are satisfied: (1) The path length for the growing wave is long enough to create a significant amplification before the wave reaches an end mirror, and (2) the reflection coefficient of the end mirrors is high enough to insure that the reflected wave experiences a net gain in amplitude upon each transit of the system. This being the case, for open systems the probability that both of these conditions will be satisfied for a given unstable wave is much less than it is in closed systems, where the propagation lengths can be very long, around and around the chamber. In such a situation in closed systems even weakly growing modes have a chance to grow to significant amplitude before they are limited by non-linear saturation effects. By contrast, in open-ended systems only much more rapidly growing instabilities would be able to rise to significant amplitude, starting from fluctuation levels. If these (rapidly growing instabilities) can be avoided by control of the plasma parameters then the plasma confinement should approach that associated with collisional processes alone. It is our contention that the history of the research into open-ended systems has provided us with examples that confirm this contention, supporting our hypothesis.

VI) Conclusion

In this paper an attempt has been made to examine the historical record of fusion research, in an admittedly selective manner, in support of the contention that there is a fundamental difference in their confinement characteristics, directly traceable to their differing topologies.

The first conclusion: closed systems are endemically prone to plasma turbulence effects of MHD and of other origin, enhancing cross-field transport and limiting their beta values. In order to produce net useful fusion power closed systems such as the tokamak and the stellarator must as a result be large and may require a complex field geometry.

The second conclusion: there are clear cases from the historical record of open systems where plasma confinement, sometimes at very high beta values, has not been dominated by turbulence but has instead appeared to approach that predicted for a quiescent state where only classical (collisional) processes determine the confinement.

With respect to the second conclusion, among the clearest cases of near-classical behavior in open systems are those where the confining field is axisymmetric. In these cases theory shows that parallel currents are zero, and that the plasma confinement is enhanced by constraints associated with the two adiabatic invariants, magnetic moment and longitudinal action. Although MHD instabilities of the interchange type (leading to transverse drift of the plasma) must be dealt with in axisymmetric mirror-type systems, theory [18] and the Gas Dynamic Trap experiment at Novosibirsk [13] has shown that there exist practical ways of dealing with this problem.

Finally, if the hypothesis proposed in this paper is accepted as proved, what does it say about possible courses of action for magnetic fusion research? Certainly it does not imply that closed systems should be abandoned as fusion devices. Such systems, with their many decades-long history of steadily improving performance, provide a defined path to net fusion power, one that will no doubt be implemented.

Taking a broader vies, however, magnetic fusion research should certainly not "put all its eggs in one basket." Open systems, particularly ones with axially symmetric magnetic fields, hold out the promise of fusion power systems that might be much smaller, and much more efficient in their use of the confining field (through higher beta limits) than any known closed magnetic system. Not only do open systems have this particular potentiality, but such systems, again because of their topology, have inherently greater flexibility in their design than do closed systems [19]. An example is their more ready adaptability for the use of direct conversion of the emerging particle streams [20].

In the fifty years since the beginnings of magnetic fusion research the desirability of the goal of safe and non-polluting power derived from a truly inexhaustible source of fuel has not diminished. It is this author's conviction that the open-topology magnetic confinement geometry has such promise for fusion power systems that it deserves a far more prominent role in fusion research than it has had.

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